Effects of helium on high frequency jet ventilation in model of airway stenosis

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Background. The addition of helium to the inspired gas may facilitate ventilation in the presence of clinically evident upper airway obstruction. However, there are no data on the effects of using a helium-oxygen mixture during high frequency jet ventilation (HFJV) in upper airway obstruction.

Methods. HFJV at a frequency of 150 min⁻¹ (driving pressure 2 bar, inspiratory time 30%) was applied to a trachea-lung model to simulate ventilation through varying degrees of fixed laryngotraheal stenosis (2.5–8.5 mm). HFJV was delivered from above, through and below the level of stenosis to simulate supraglottic, transglottic and infraglottic administration. Measurements of distal tracheal pressures were repeated for each route at steady state for each stenosis diameter using both 100% oxygen and helium-oxygen (50% oxygen, 50% helium). The output of the ventilator was measured during operation on oxygen and helium-oxygen.

Results. Peak, mean and end-expiratory pressures were greater during simulated supraglottic HFJV than during transglottic and infraglottic HFJV, and pressures increased markedly as the diameter of the stenosis decreased for all routes of ventilation (P<0.001). Generated pressures during HFJV using helium-oxygen and 100% oxygen were very similar overall, although reductions in pressures were observed during ventilation with helium-oxygen via the transglottic and transtracheal routes at stenosis diameters <4 mm (P<0.05). However, HFJV with the helium-oxygen mixture increased the delivered gas volumes by ~18%.

Conclusions. Using 50% helium-oxygen during HFJV in the presence of airway stenosis allows an 18% increase in minute volume at generated airway pressures which are the same as or lower than those when using 100% oxygen.


Keywords: airway, obstruction; gases non-anaesthetic; model, gas dynamics; ventilation, high frequency jet

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Airway management in the presence of upper airway stenosis is challenging for the anaesthetist because delivery of oxygen and anaesthetic gases during surgery may be limited by the stenosis. The use of conventional modes of ventilation via a tracheal tube is often impossible because of the stenosis, and high frequency jet ventilation (HFJV) is an alternative.1,2 The use of HFJV in this situation is controversial because of the potential risk of barotrauma, particularly when the gas under high pressure is delivered below the stenosis in a situation where gas outflow may be impared. HFJV can be applied using a small-bore catheter from above the stenosis (supraglottic ventilation), passed through the stenosis (transglottic ventilation)3 or delivered via cricothyrotomy below the level of stenosis (transtracheal ventilation).4,5 The last route has the advantage that it avoids potential obstruction of the stenosis by the jet cannula, but cricothyroid cannulation is required.

Helium has a low density and hence has been added to the inspired gas mixture to facilitate conventional ventilation in the presence of upper airway obstruction as well as in conditions such as asthma affecting the lower airways.6,7 Because helium improves gas movement in conditions of
turbulent flow, it may enhance diffusion and elimination of carbon dioxide, improve distribution of ventilation and ventilation–perfusion matching in the areas of long time constants and improve distal gas mixing and diffusion. These benefits may also be useful during HFJV.\textsuperscript{7, 8} We have previously described HFJV using oxygen and air in a bench-top model of upper airway stenosis.\textsuperscript{9} The effect of helium in this situation is unknown and we hypothesized that the addition of helium to the driving gas during HFJV would result in lower airway pressures, depending on both the route of HFJV administration and the stenosis diameter. Therefore in this study we investigated the effect of 50% helium–oxygen in a modified model of upper airway stenosis.

Materials and methods

The lung–trachea model previously described\textsuperscript{9} comprised a Siemens Test Lung 190 (6006832E037E) (Siemens AG, Munich, Germany) connected to a corrugated plastic tube (15 cm long, 22 mm diameter) representing the trachea. In the proximal part of the ‘trachea’ a connector of differing diameter (2.5, 3.0, 3.5, 4.0, 4.5, 5.5, 6.5, 7.5 and 8.5 mm) was attached to simulate varying degrees of airway stenosis (Fig. 1). All connectors were of the same length. The lung–trachea model incorporates ports allowing distal tracheal pressure measurements and application of jet ventilation from below the level of stenosis.\textsuperscript{9} Above-stenosis ventilation (ASV) was delivered from the jet cannula (2 mm internal diameter, 12 cm long) aligned precisely proximal with the opening of stenosis at a constant distance (11 mm). A plastic catheter (15 cm long, 2 mm internal diameter) was attached to the jet cannula and fed through the stenosis to simulate the trans-stenotic ventilation (TSV). Thus ASV, TSV and BSV were used to represent supraglotic, transglottic and transtracheal ventilation, respectively. HFJV was delivered using a Bromsgrove humidified jet ventilator (Penlon Ltd, Abingdon, UK) connected to a Model 3500HL Sechrist air–oxygen mixer (Sechrist Industries Inc., Anaheim, CA, USA) calibrated to deliver a 50% helium–oxygen mixture. The concentration of oxygen was confirmed using a Datex-Ohmeda S/5 gas analyser (Datex/Ohmeda Ltd, Hatfield, UK). Recordings were made using the pressure monitor incorporated into the ventilator, and end-expiratory pressures were recorded at steady state using the pressure monitor incorporated into the ventilator, and each measurement was repeated three times.

The output of the Bromsgrove jet ventilator was quantified using the time taken to fill a glass vessel of calibrated volume (5.4 litres) under water with 100% oxygen and 50% helium–oxygen mix. Measurements were recorded nine times for each gas and the minute volume was derived.

Statistical analysis was performed using Friedman analysis of variance (ANOVA) for (within-group) comparisons between stenosis diameter, and Kruskal–Wallis ANOVA for (between-group) comparisons between gas types. All tests were performed using SPSS for Windows (release 11.01, 2001). A P-value < 0.05 was accepted as being statistically significant.

Results

Peak, mean and end-expiratory pressures (PIP, MAP and EEP) during HFJV applied from above, through and below the stenosis are shown in Figure 2. The pattern of a significant increase in all measured pressures as the stenosis diameter decreased was similar for all HFJV routes (P < 0.001 for all routes of ventilation). Pressures were consistently higher with ASV at all stenosis diameters. PIP and MAP were low (<10 cm H\textsubscript{2}O) during TSV at stenosis diameters >4.5 mm and during BSV at stenosis diameters >3.5 mm, respectively. However, at smaller diameters there was a sharp increase in PIP, MAP and EEP, particularly during TSV. No measurements were possible at a stenosis diameter of <3.5 mm using TSV because the jet catheter appeared to occlude the airway; the measured pressure exceeded the default settings of the ventilator and so HFJV was not possible.

Pressures recorded during HFJV with helium–oxygen were similar to those obtained using 100% oxygen at stenosis diameters >4 mm irrespective of delivery route (ASV, TSV or BTV). However, PIP, MAP and EEP were significantly lower during BSV and TSV at diameters <4 mm (all P < 0.05). EEP was lower during ASV at a stenosis diameter <4.0 mm during SGV (P < 0.05), although the absolute pressure differences were small in all these situations. However, the calculated output of the Bromsgrove ventilator was ~18% higher during ventilation with helium–oxygen (Table 1).

Table 1 Measured output of the Bromsgrove humidified jet ventilator during HFJV with 50% helium–oxygen and 100% oxygen. Data presented as mean (SD).

<table>
<thead>
<tr>
<th>Stenosis Diameter (mm)</th>
<th>50% helium–oxygen</th>
<th>100% oxygen</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.0</td>
<td>14.28 (0.28)</td>
<td>17.00 (0.27)*</td>
</tr>
<tr>
<td>3.5</td>
<td>22.68 (0.45)</td>
<td>19.06 (0.30)*</td>
</tr>
</tbody>
</table>

*P < 0.001 between groups
Fig 2  (A) Peak, (B) mean and (C) end-expiratory pressures measured during HFJV delivered via supraglottic, transglottic and transtracheal routes. Data are presented as mean (95% confidence limits). All pressures were greater during supraglottic HFJV, and generated pressures increased as the diameter of the stenosis decreased \(P<0.001\) for all routes of ventilation. There were few significant differences in pressures when comparing HFJV with helium–oxygen or 100% oxygen during above stenosis ventilation (ASV). Pressures were lower during through stenosis (TSV) and below stenosis (BSV) ventilation at stenosis diameters <4 mm, although absolute differences were small. HFJV was impossible during TSV at stenosis diameters 2.5 and 3 mm because of occlusion of the airway by the jet cannula. *\(P<0.05\) between helium–oxygen and oxygen.
Discussion
There was a small but significant reduction in airway pressures using a helium–oxygen mixture compared with 100% oxygen during HFJV via the TSV and BSV routes. Pressures were consistently higher during ASV, consistent with our previous data,9 with little reduction when helium–oxygen was administered. Delivered volumes were ~18% greater during HFJV with helium–oxygen.

In clinical practice the transglottic and transtracheal routes of delivery of HFJV represented by TSV and BSV are mechanically very similar, as in both situations ventilation is actually delivered distal to the stenosis and flow through the stenosis occurs only in one direction—outwards. However, effective airway diameter is reduced during TSV by the jet catheter, which prevented effective ventilation at low stenosis diameters. This would explain why the pressure–stenosis curves describing the relationship between airway pressure and stenosis diameter are essentially parallel (Fig. 2) but shifted towards the right because effective airway diameter is reduced by the presence of the jet catheter. During TSV at stenosis diameters <3 mm the effective airway diameter was so small and generated such high pressures that the cut-off mechanism of the ventilator was activated and ventilation ceased before the system reached steady state. Although measurement of alveolar pressure would be preferable, this is impossible given the limitations of our lung model compared with the human lung, and distal ‘tracheal’ pressure is commonly used in clinical practice. However, the absolute values of tracheal pressures during ASV and TSV at small stenosis diameters suggest an obvious potential for barotrauma.

The effects of helium–oxygen on airway pressure in this experiment were less than we had anticipated. During ventilation in humans most of the resistive pressure drop occurs between the glottis and the 10th generation of the airways. Flow here is turbulent and therefore varies with the density of the inspired gas. Because helium is less dense than nitrogen, its Reynolds number is several-fold lower and laminar flow is likely to prevail during gas movement at significantly higher flow rates. Reduced resistance to flow means that a lower pressure is required for the same volume of gas movement, which is particularly relevant in the presence of airway stenosis. Based on previous data we expected that a helium concentration of 50% would reduce the density of the gas mixture and facilitate ventilation. In an animal study, Katz and colleagues10 used 40% helium–oxygen and, although improvements in gas exchange were not observed, a reduction in oscillation amplitude during 40% helium–oxygen ventilation was reported, reflecting facilitation of ventilation. One possible explanation for the lack of effect of helium in this study is that the helium concentration used was too low for the expected reduction in airway pressures to be demonstrated. An increase in the helium concentration in the inspired gas has the obvious drawback of reducing the fraction of inspired oxygen. If helium is to have any clinically beneficial effect it must occur at concentrations allowing its use in patients with high oxygen requirements, who may be potentially difficult to oxygenate. Therefore, although a greater effect may have been demonstrated using a higher inspired concentration of helium, we decided to conduct these experiments using a 50% helium–oxygen mixture, which we considered clinically relevant, and indeed a similar value has been used by other workers.8

We also recognize the limitations of our model in terms of extrapolation to the human anatomy and physiology. The effects of changes in elastance on a bench model system examining the cough manoeuvre have shown that flow characteristics of the system may be altered by changes in the elastance of the model.11 However, all our measurements were made at steady state, and the compliance of the system was found to be static over a range of test lung conditions (preliminary experiments; data not shown). Furthermore, the simplicity of the model allowed us to perform an accurate examination of the effects of stenosis diameter, route of ventilation and the use of helium without the confounding effects of changes in elastance of the system.

In addition, the actual volume of the pulse of gas delivered during jet ventilation is notoriously difficult to measure. The majority of HFJV ventilator manufacturers do not monitor this parameter at all, although some include estimated tidal/minute volume. Even so, the system is calibrated for gas of density similar to that of air or oxygen and application of helium as a driving gas renders it inaccurate. Consequently, the generated output of the ventilator during operation on helium–oxygen is hard to predict. Regardless of the manufacturer or model, before the pulse of gas is delivered to the patient, the supplied gas will pass through the delivery system where it has to flow through a fixed or variable calibrated orifice and tubing. This flow will be dependent on density of the driving gas. For this reason it would be very difficult, if not impossible, to design a ventilator capable of delivery of the same volume of heliox or oxygen–air mixture at the same driving pressure and inspiratory time. However, in our calibration experiments, the application of helium resulted in an 18% increase in delivered minute volume for all three routes of administration of HFJV and we would expect that ventilation would be affected in a proportional manner for all routes of delivery, but this was not quantifiable in the context of the airway stenosis model. Therefore the potential reduction in airway pressures using helium–oxygen may have been masked by the higher gas volumes delivered, and although the absolute reduction in airway pressure was small, the combination of higher delivered volume at lower airway pressures suggest that this gas mixture might be useful in clinical practice.

The other consistent finding in this study was that airway pressures during HFJV delivered via ASV were consistently
higher than during TSV and BSV. The reason for this is unclear, but possible explanations include intermittent obstruction of gas outflow by the jet itself or increased entrainment of room air during ASV compared with TSV or BSV. However, as discussed above, delivered minute volume was not measured during each method of ventilation in the model. We also noted no differences in airway pressures between helium–oxygen and oxygen during ASV, and if significant entrainment of room air were occurring the actual delivered concentration of helium would be decreased because of dilution with entrained room air. This is difficult to ascertain from these data because delivered gas concentrations were measured at the ventilator rather than within the test lung, but might explain the lack of effect observed with helium. Future studies are planned to address these observations, and further investigation is required to quantify the relationship between possible air entrainment and the role of a lower density gas such as helium. Whilst recognizing the limitations of this model, the pressures generated during ASV over the range of stenosis diameters would be excessive if delivered to patients, especially at stenosis diameters <4.5 mm, suggesting that TSV or BSV might have advantages in clinical practice. These data suggest no advantage of helium during ASV, but there may be advantages of reduced airway pressures with a simultaneous increase in delivered ventilation at low stenosis diameters during TSV and BSV.

In summary, these results suggest that HFJV with 50% helium–oxygen allows increased minute ventilation in the presence of a modelled airway stenosis with the same or lower airway pressures. Airway pressures were consistently lower when HFJV was applied from below the stenosis than when it was applied from above, particularly at stenosis diameters <4.0 mm.

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References
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